On the mechanism of prompt emission of gamma-ray bursts.

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We propose a model in which prompt γ emission of gamma-ray bursts is the synchrotron radiation of electron-positron plasma in the ordered magnetic field in the direct vicinity of horizon of a young black hole formed in the core collapse of a massive star. This mechanism can naturally explain high degree of polarization of the γ-ray flux and hard low energy photon spectral index. Interaction of γ-quanta with ambient matter provides a mechanism of formation of relativistic ejecta which are responsible for the γ-ray burst afterglows.

Recently established connection between gamma-ray bursts (GRB) and Type Ic supernovae [1, 2] supports the assumption that long GRBs can be produced in the core collapse of massive stars [3, 4]. The collapse of high mass ($M_\star > 40 M_\odot$) stars can result in direct production of black holes of masses $M_\bullet \sim 10 M_\odot$ [5]. Subsequent accretion of the stellar material onto the newly born black hole can serve as a "central engine" of GRBs (see e.g. [3]).

In most of the GRB models (which can be called "fireball-type" models, see [6] for a recent review) the nature of the central engine of a GRB remains unclear because prompt γ emission is produced at a large distance from the center. This is unavoidable if one supposes that total energy of a GRB is deposited into kinetic energy of particles in a small volume of the size about the size of central engine. In this case particle density is so high that the optical depth for the γ-ray photons is $\tau \gg 1$. The spectrum and temporal characteristics of the prompt γ emission are not related to the properties of the central engine, but are, in fact, determined by the properties of the shocks at a distance $R_{fin} > 10^{14}$ cm [6] at which matter becomes transparent to γ rays.

The fireball-type models of GRBs have certain problems in explaining characteristics of the prompt γ-ray flux, such as the very steep low-energy spectral index α of BATSE GRBs [7] or the high degree of polarization of prompt γ emission detected by RHESSI [8] (see [9, 10] for discussion of this subject). Both problems arise because the emission region is not compact and it is difficult to expect that the γ ray synchrotron emission can be self-absorbed or the magnetic field can be ordered on the distance scale $\sim R_{fin}$.

The fact that properties of γ-ray emission are unrelated to the physics of the central engine holds only for the models in which GRB energy is stored at some stage as kinetic energy of relativistic particles (in this respect models which involve pulsars [11], or electromagnetic outflows from a black hole [12] are similar to the fireball model). However, if the central engine of GRB is a black hole, the energy can be stored in the form of the black hole rotational energy [3]. The problem of "compactness" can be overcome if one considers a mechanism of conversion of this rotation energy directly into γ-ray flux, without intermediate "particle dominated" phase. In this case the prompt emission of a GRB can originate from a very compact region of the size about the gravitational radius of a black hole (one still has to assume sufficient beaming of the γ ray flux so that the pair production in $\gamma\gamma$ interactions is suppressed). In such scenario the total energy, duration and variability of GRB would be directly related to the physical parameters of the central engine.

In what follows we propose a model in which prompt emission of a GRB is produced in the vicinity of horizon of a young stellar mass black hole. We show that combined effect of pair production by γ quanta in strong magnetic field and absorption of particles by the black hole horizon can lead to formation of a relatively low density layer of e^+e^- plasma close to the horizon. Electrons and positrons accelerated in the vicinity of horizon by rotation-induced electric field suffer from severe energy losses so that all the work done by external field is immediately radiated in the form of MeV γ rays. The γ rays are emitted in a highly anisotropic way: in a form of two oppositely directed beams with the opening angles $\theta \sim 1/\Gamma_e$ where $\Gamma_e \sim 10\div 100$ is the typical gamma-factor of electrons. Subsequent interaction of the γ-ray beams with background matter can give rise to a rapid deposition of a fraction of the beam energy into the surrounding matter and production of relativistic ejecta much like in the fireball models. Thus, the model under consideration retains the advantages of the "standard" model of GRB afterglows but relates the prompt γ emission to the mechanism of production of relativistic outflows close to the black hole.

Our set up is close to the one considered in [3, 4]: the core of a massive, rapidly rotating star collapses to form a $M_\bullet \sim 10 M_\odot$ black hole. The outer parts of the core can form an accretion disk/torus which can support strong magnetic field $B_\bullet \geq 10^{12-13}$ G. An estimate of the strength of magnetic field can be obtained from the "equipartition argument" (assumption that the energy densities of the magnetic field and radiation are of the same order). If the typical luminosity of the central engine is $L_\bullet \sim 10^{48}$ erg/s and the size of the emission region is $R \sim R_\bullet$, where $R_\bullet = 2GM_\bullet = 3\times 10^6 (M_\bullet/M_\odot)$ cm,

the equipartition magnetic field is

$$B_\bullet \sim 10^{12} \left[\frac{L_\bullet}{10^{48}\text{erg/s}}\right]^{1/2} \left[\frac{10M_\odot}{M_\bullet}\right] \text{ G} \tag{1}$$

(much stronger magnetic field was supposed in [3] because the assumed mechanism of extraction of rotational energy of the black hole was different from the one considered below).

If the magnetic field is produced by the accretion disk/torus, the typical scale of spatial variations of the field is about the size of the disk which is larger than the size of the black hole. The magnetic field is ordered at the length scale $R \sim R_\bullet$ [13]. Synchrotron radiation from electrons and/or positrons in this magnetic field can provide reasonable explanation for the observed polarization of the prompt γ-ray emission.

The energy of electrons which emit in MeV band in the above magnetic field is

$$E_e = 7.3 \times 10^6 \left[\frac{\epsilon_\gamma}{1 \text{ MeV}}\right]^{1/2} \left[\frac{10^{12}\text{ G}}{B_\bullet}\right]^{1/2} \text{ eV.} \tag{2}$$

The propagation distance of such electrons is just about $\lambda_{sy} = 4 \times 10^{-7} \left[10^{12} \text{ G}/B_\bullet\right]^{3/2} \left[1 \text{ MeV}/\epsilon_\gamma\right]^{1/2}\text{cm} \ll R_\bullet$. This means that electrons should be continuously accelerated near the black hole horizon.

Electric field which accelerates electrons can be generated by various mechanisms by the accretion disk and by the black hole itself. In fact, rotational drag of external magnetic field near horizon leads to the generation of electric field whose strength is $E_\bullet \sim (a/M_\bullet)B_\bullet$ ($a \le M_\bullet$ is the rotation moment per unit mass) [13]. Electron acceleration rate in the electric field whose strength is comparable to $B_\bullet$ can be estimated as $dE_e/dt = qeB_\bullet$ where $q \le 1$ is the parameter which characterizes effectiveness of the acceleration process. Maximal energy of electrons is determined by the balance between acceleration and energy loss rates. If electric field is not aligned with magnetic field, the energy loss rate coincides by order of magnitude with synchrotron loss rate [14]. In this case the maximal energy of electrons is

$$E_{max} = \left[\frac{3qm_e^4}{2e^3B_\bullet}\right]^{1/2} \sim 3 \times 10^7 q^{1/2} \left[\frac{10^{12}\text{ G}}{B_\bullet}\right]^{1/2} \text{ eV.} \tag{3}$$

One can see that we have to suppose that the acceleration rate is quite high $q \sim 0.1$ in order to continuously supply electrons which radiate in MeV band. The rough estimate (3) does not take into account the geometry of electromagnetic field near the horizon. Since we are dealing with ordered electric and magnetic field configuration, the energies of electrons (and, correspondingly, the spectrum of synchrotron radiation) depend strongly on the mutual orientation of magnetic field $\vec{B}_\bullet$, electric field $\vec{E}_\bullet$ and particle velocity $\vec{v}$. It is natural to expect that the angular distribution of the power and of the spectrum of the synchrotron radiation is highly anisotropic.

Since the particles are accelerated along (or oppositely to) the direction of the external magnetic field and since the typical gamma-factors of electrons and positrons are $\Gamma_e > 10$ the synchrotron flux is concentrated within two oppositely directed cones with opening angle $\theta < 1/\Gamma_e \sim 5^o$. Beaming within a narrow cone explains why the pair production in $\gamma\gamma$ interactions does not prevent the MeV γ-rays to escape from the emission region (see [6]).

Contrary to neutron stars, black holes can not support their own magnetosphere. Indeed, free charges can not be emitted from the black hole surface, they can only be accreted from infinity or generated *in situ*. If the magnetic field near horizon is strong, the γ-quanta can supply free charges due to the pair production in external magnetic field. Propagation length of a γ-quantum of energy ϵ_γ in magnetic field $B_\bullet$ exponentially decreases with energy, $\lambda_{B\gamma} \approx 10^{-6} \left[10^{12} \text{ G}/B_\bullet\right] \exp\left(8m_e^3/(3B_\bullet\epsilon_\gamma)\right)$ cm, and reaches $\lambda_{B\gamma} \sim R_\bullet$ when ϵ_γ rises to

$$\epsilon_{\gamma\to e^+e^-} \approx 0.1\frac{m_e^3}{B_\bullet} = 2 \times 10^6 \left[\frac{10^{12}\text{ G}}{B_\bullet}\right] \text{ eV} \tag{4}$$

Thus, γ-quanta which form a high-energy tail of the synchrotron spectrum $\epsilon_\gamma > \epsilon_{\gamma\to e^+e^-}$ can not leave the emission region, they are immediately converted into e^+e^- pairs. In fact, if the direction of propagation of photons is inclined at angle θ_γ to the direction of magnetic field, the threshold of pair production can be higher by a factor of $1/\theta_\gamma$, as compared to (4). The spectrum of γ-rays which escape from the acceleration region depends strongly on the orientation of an observer relative to the direction of magnetic field: harder spectra are observed at smaller viewing angles.

The pair production increases the density of e^+e^- plasma near the horizon. At the same time, absorption of particles by the horizon leads to the decrease of the plasma density. The density of charge right near the horizon is determined by the competition between pair production and accretion rates. If the plasma density in the acceleration volume exceeds certain critical density (see [15])

$$n_{cr} \sim \frac{B_\bullet}{eR_\bullet} = 10^{15} \left[\frac{B_\bullet}{10^{12}\text{ G}}\right] \left[\frac{10M_\odot}{M_\bullet}\right] \text{ cm}^{-3} \tag{5}$$

redistribution of charges in the vicinity of horizon can lead to the neutralization of the strong parallel electric field and decrease in the efficiency q of the acceleration process. Minimal time scale at which the charge redistribution can happen is about the light crossing time of the acceleration region. This scale defines the minimal variability time of the system

$$T_{var} \ge \frac{R_\bullet}{c} = 10^{-4} \left[\frac{M_\bullet}{10M_\odot}\right] \text{ s.} \tag{6}$$

If the back reaction of freshly created e^+e^- pairs on the external electromagnetic field reduces the efficiency of acceleration q, the typical energy of γ quanta decreases as $\epsilon_\gamma \sim q$. The decrease in energy of synchrotron quanta leads to the decrease in the pair production rate since most of the quanta have energies below the pair production threshold (4). In the absence of the pair production the density of e^+e^- plasma will decrease rapidly because all the plasma falls behind the horizon. But as soon as the plasma density decreases, the strong electric field induced by the black hole rotation can again accelerate particles more efficiently. If the acceleration efficiency rises back, the energies of electrons and positrons increase and synchrotron γ-quanta can again produce pairs in magnetic field. Thus, there is a "critical" regime of operation of the central engine in which the plasma density is close to the value given by Eq. (5).

The particle density (5) is significantly lower than the density in the central engine estimated in the fireball model. In the fireball model one assumes that the total energy of the GRB $E_{tot} \sim 10^{52}$ erg is initially deposited into matter particles in the volume of the size defined by the variability time scale $R_{var} \sim 10^7$ cm. In this case one obtains the particle density $n_{fb} \sim E_{tot}/(R_{var}^3 \Gamma_{fb} m) \sim 10^{31\div 34}$ cm$^{-3} \gg n_{cr}$ ($\Gamma_{fb} \sim 10^{2\div 3}$ is the typical gamma-factor of the particles and m is the mass of the particles, which is equal to electron mass in the case of a fireball without barions [16] and to the proton mass in the case of a "cannon ball" [17]). At such high particle density the fireball is not transparent to the γ radiation. The optical depth is $\tau = \sigma_T n_{fb} R_{var} = \sigma_T E_{tot}/(R_{var}^2 \Gamma_{fb} m_e) \sim 10^{15\div 18}$ (σ_T is the Thomson cross section). That is why one has to suppose that the observed γ emission originates from the distances much larger than the size of the central engine: the optical depth decreases as $\tau \sim R^{-2}$ and reaches $\tau \sim 1$ when the size of the fireball (or cannonball) becomes $R_{fin} \sim 10^{14\div 16}$ cm. The mechanism under consideration differs from the fireball model: work done by rotation-induced electric field on a charged particle is not used to increase the particle energy. Instead, it is immediately radiated in the form of γ quanta. That's why one does not need to assume large particle density in the central engine.

When the central engine operates in the "critical" regime (5) luminosity of the black hole can be estimated as follows. Since the acceleration rate balances the energy loss rate, each electron radiates with power $P_e \sim qeB_\bullet = 1.4 \times 10^{13} q (B_\bullet/10^{12}$ G) erg/s. The total number of electrons in the acceleration volume is $N = (4\pi/3) R_\bullet^3 n_{cr}$. Thus, the total luminosity is

$$L_{cr} = \frac{4\pi}{3} q R_\bullet^2 B_\bullet^2 = 1 \times 10^{48} q \left[\frac{B_\bullet}{10^{12}\ \mathrm{G}}\right]^2 \left[\frac{M_\bullet}{10 M_\odot}\right]^2 \ \mathrm{erg/s}. \tag{7}$$

If the direction toward an observer lies inside the emission cone with opening angle $\theta = 1/\Gamma_e \sim 0.1$, the inferred equivalent spherical luminosity is $L_{sph} = \Gamma_e^2 L_{cr} \sim 10^{50}$ erg/s.

Compactness of the emission region in the model under consideration rises the question of possible self-absorption of the radiation. The self-absorption length, which is the inverse of the absorption coefficient is given by [20]

$$\lambda_{sa} \sim 0.1 \frac{m_e^4 \epsilon_\gamma^3}{e^4 B_\bullet^2 E_e n_{cr}} \tag{8}$$

Substituting n_{cr} (5) and E_e (2) into this equation and taking λ_{sa} to be about the size of the emission region $\sim R_\bullet$ we find that the self-absorption becomes important for photons with energies $\epsilon_\gamma \leq \epsilon_{sa}$ with

$$\epsilon_{\mathrm{sa}} \sim 30 \left[\frac{B_\bullet}{10^{12}\mathrm{G}}\right]^{1/5} \ \mathrm{keV}. \tag{9}$$

Self-absorption of the low-energy part of γ ray spectrum can be responsible for the very hard low-energy spectral index $\alpha < -2/3$ of about a quarter of BATSE GRBs [7]. The possibility that the hard low-energy spectra can be due to the self-absorption in the source was considered in [21]. However, within the fireball-type models one has to assume unrealistic physical conditions in the shock [22] if one tries to find the self-absorption for photons in the energy range (9).

GRB afterglow and connection with supernovae explosions. The fate of the γ-ray beam produced in the central engine depends on the background through which it propagates toward an observer. The background in the vicinity of a newly born black hole is determined by the previous evolution of a progenitor star. Spectral characteristics of Type Ib/c supernovae (which are thought to be associated with GRBs) imply that progenitor stars experience an extended period of mass loss before the explosion and completely loose their hydrogen envelope [18]. The "bare core" progenitor star of Type Ib/c supernova should be surrounded by the extended region containing matter ejected in the stellar wind.

At the distance scale of the order of size of the core, $R \sim 10^{10}$ cm, the γ-quanta emitted from the black hole can interact with the rests of the progenitor star while at larger scales $R \sim 10^{15}$ cm the γ-ray beam power can be absorbed in interactions with the wind particles. The geometry of the inflowing material is expected to be highly complicated. Rotation of the progenitor leads to faster infall of the polar regions as compared to the equatorial regions [4]. Therefore we have to consider two possibilities: when the γ-ray beam can escape from the collapsed core and when the power of the beam is absorbed in the rests of the core. Of course, it can happen that just a fraction of the γ-ray power is absorbed in the core.

If the γ-ray beam interacts mostly with the extended wind region around the progenitor star, the propagation

distance of the γ-quanta can be estimated as follows. Assuming the asymptotic velocity of the wind $v_\infty \sim 10^3$ km/s and the mass loss rate $\dot{M}_{wind} \sim 10^{-5} M_\odot$/yr, we can estimate the density of background particles at the distance D from the progenitor as

$$n_{wind} \approx 3 \times 10^{11} \left[\frac{\dot{M}_\star}{10^{-5} M_\odot/\mathrm{yr}} \right] \left[\frac{10^{12}\ \mathrm{cm}}{D} \right]^2\ \mathrm{cm}^{-3}. \tag{10}$$

The total cross section of interaction of γ quanta with wind electrons can be estimated as $\sigma \sim \sigma_T$. The mean free path $\lambda_{\gamma,wind} = (\sigma n_{wind})^{-1}$ of γ-rays is equal to

$$\lambda_{\gamma,wind} \sim 1.5 \times 10^{13} \left[\frac{10^{11}}{n_D} \right]\ \mathrm{cm} \tag{11}$$

This means that significant part of the γ-ray flux can be absorbed during propagation through the wind zone. In this case a patch of the wind which is situated on the way of the γ beam will receive an energy $E_{tot} \sim L_{cr} T_{GRB}$ where L_{cr} (7) is the beam power and T_{GRB} is the duration of the GRB. Assuming $T_{GRB} \sim 10^{1 \div 2}$ s we find that the wind patch can acquire total energy $E_{tot} \sim 10^{49 \div 50}$ erg. If we compare this energy to the rest energy of the wind particles contained within the volume of the size $D \sim 10^{13}$ cm, $E_{rest} = Mc^2 \sim (4\pi/3) D^3 n_{wind} m_p = 10^{47}$ erg (for the value of n_{wind} given in (10)), we find that the transmitted energy is enough to accelerate the patch of the wind to the speed comparable to the speed of light. In this case the situation is similar to the one assumed in the fireball model: large energy $E_{tot} \gg Mc^2$ deposited into kinetic energy of the matter will be subsequently radiated as the GRB afterglow. Different models of evolution of relativistic ejecta, like relativistic fireball models [16], or cannon ball model [17] can provide satisfactory fits to the properties of GRB afterglows.

If one or both γ-ray beams hit the rests of the progenitor star, rather than escape into the wind zone, the energy of the beam can be absorbed within the star. As a result a relativistic jet will form inside the (rests of the) collapsing core. This jet can give rise to the jet-induced supernova explosion [19]. The jet mechanism of supernova explosions can be generally valid in the case of highly asymmetric explosions of very massive stars (see [5]). Note that if the initial magnetic field near the black hole horizon is higher than 10^{13} G, the typical gamma-factor of electrons is $\Gamma_e < 10$ (3). In this case the synchrotron emission is almost isotropic. The power $L_{cr} \sim 10^{50}$ erg/s (7) is emitted in the form of γ-quanta with energies below the pair production threshold $\epsilon_{\gamma \to e^+ e^-} \leq 0.1$ MeV (4). This powerful γ-ray flux can be absorbed in the outer parts of the collapsing core. Absorption of this isotropic flux can lead to the bounce and subsequent expansion of the accreting material. In this case the behavior of ejected matter should be similar to the one considered in the "dirty fireball" or "hypernova" model discussed in Ref. [3].

To summarize, we have considered a mechanism of the prompt γ-ray emission of GRBs in which the beamed γ-ray flux is produced by electrons and positrons propagating in the strong magnetic field field $B_\bullet \sim 10^{12}$ G in the vicinity of a young black hole formed in the core collapse of a massive star. This mechanism can naturally account for the high degree of polarization and hard low energy spectral index of a part of GRBs. Since the γ-ray flux originates directly in the central engine of GRB, observed characteristics of the GRBs are directly related to the physical properties of the central engine. The GRB photons are emitted from the vicinity of horizon where nonperturbative effects of General Relativity are important. Besides, the synchrotron γ-quanta are emitted by electrons in magnetic field whose strength is just an order of magnitude below the critical value $B_q = 4.4 \times 10^{13}$ G at which quantum effects set on. Thus, within the considered model, prompt emission of GRBs can provide an interesting laboratory for General Relativity and strong magnetic field physics. γ-quanta emitted form the central engine of GRB can be partially absorbed during the propagation through the extended wind zone around the progenitor star or through the accreting/ejected matter. Interaction of the γ-rays with background particles leads to production of relativistic ejecta ("fireballs") from the central engine which are responsible for the GRB afterglows.

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